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*Interim Technical Report*

## EVALUATION OF RETROFIT APPLICATIONS OF NUMERICAL CONTROLS

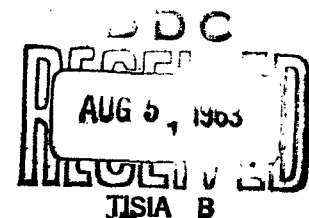
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## I INTRODUCTION

In 1957 Stanford Research Institute completed a preliminary investigation of the technical and economic feasibility of retrofitting numerical controls to machine tools in service.<sup>1</sup> This study, conducted for the Industrial Planning Division of the (then) Bureau of Aeronautics, indicated that retrofit was a practical means of applying numerical control to conventional manually controlled tools. It also indicated that the acquisition cost level for retrofitted numerical control systems was generally lower than that for procurement of new numerically controlled tools. Because of the early state of the art of numerical controls at that time, very few retrofitted machines were in regular service. As a consequence, information for retrofitted machine tools in production use was almost entirely lacking, and the study results, therefore, were based largely on estimated data.

The current retrofit evaluation program of the Industrial Division of the Bureau of Naval Weapons (BuWeps) was conceived and implemented primarily to obtain valid comparative data concerning the cost and performance of retrofitted machines in production service. The program was initiated in 1959 with contracts between BuWeps and four major airframe contractors to procure, operate, and evaluate four different retrofitted numerically controlled machine tool systems, as follows:

Contractor	Machine Tool	Control System
Grumman Aircraft Engineering Corp. (GAEC)	Kearney & Trecker (K&T) #4 knee-type milling machine	True-Trace
McDonnell Aircraft Corp. (MAC)	K&T bed-type horizontal milling machine	Bendix
North American Aviation, Inc. (Columbus Division) (NAAC)	Cincinnati bed-type horizontal milling machine	Cincinnati
Chance Vought Aircraft, Inc. <sup>2</sup> (CVA)	Cincinnati bed-type 3-spindle vertical milling machine	Thompson Ramo Wooldridge (TRW)

<sup>1</sup> Retrofit Applications of Numerical Controls for Machine Tools, SRI Project No. IU-1896, Contract NOas 57-101-c, December 1957.

<sup>2</sup> Now Chance Vought Aeronautics Division of Ling-Temco-Vought Corp.

A supplementary study contract with Stanford Research Institute provides for the development of uniform evaluation methods and criteria, the review and supplementing of the contractors' evaluations, and the consolidation and analysis of resulting information and data.

The procurement phase of the program is now essentially complete. All four of the Navy-owned machine tools have been retrofitted with numerical controls and three have been reinstalled for operation in the respective contractors' plants. Two of the four machines have been placed in regular manufacturing service, but as yet their production evaluations are not complete and comparative production data are not available.

This interim report is being submitted to apprise BuWeps of the results of the program to date, pending completion of the production evaluation phase and receipt of the contractors' reports on all four machines. It is now expected that the Institute's final report on the results of the entire program will be completed early in 1962.

## II SUMMARY AND CONCLUSIONS

Although the major objective of the BuWeps retrofit program--the production evaluation--has yet to be achieved, the completion of the procurement and testing of four major machine tools, each retrofitted with a different numerical control system, has developed valuable experience and practical results concerning cost and performance. The program thus far has illustrated in practice the feasibility of retrofitting as a means of modernizing and upgrading existing machine tools.

The findings of the Institute's previous study have generally been substantiated. Many of the conclusions developed earlier have now been amplified and demonstrated. Moreover, certain important considerations have been revised on the basis of the specific examples of the four retrofit systems procured for the program.

### Technical Feasibility

The technical feasibility of retrofitting existing machines with numerical controls has been further substantiated by this program. The four machines, varying widely as to design, age, and condition, were retrofitted in spite of various limitations relative to one or more of these factors. None of the technical problems encountered were insurmountable, even though the basic configuration had to be extensively altered in three of the four machines.

Three of the resulting retrofits are successful; the outcome of the fourth machine (CVA) is still uncertain. All machines met the performance requirements specified by the contractors. Three machines (MAC, NAAC, and CVA) have been tested to date according to the National Aircraft Standards (NAS) procedures and have either met (though only marginally in the case of the CVA machine) or exceeded all specification requirements commonly applied to numerically controlled machine tools procured for use in the aerospace industries.

### Advantages of Numerical Control

All of these four machines have been given greatly enhanced capabilities by conversion to numerical control. All cutting motions, other machine functions, and certain auxiliary functions can now respond automatically to programmed instructions on tape or other control media.

The following principal characteristics of numerical control should therefore be attainable:

1. Increased work flexibility and capability for complex machining
2. Better accuracy and consistency of production
3. Greater productivity
4. Shorter manufacturing cycle time
5. Reduced manufacturing costs

Comparative evaluation data are being assembled to illustrate quantitatively the magnitude of these benefits in production.

#### Advantages Due to Retrofit

In their original condition these machines represented limited capabilities which usually confined them to certain classes of machining work requiring relatively low accuracy. Two of the machines were very old and in poor condition; they were worth only a few hundred dollars as scrap. The other two machines, though newer, had inherent defects which restricted their capability for precision work, though these were serious in only one machine. Generally speaking, then, at least three of these machines are known to have been difficult to find suitable work for and difficult to use in such work.

Following retrofit, however, all machines demonstrated test performances which should enable them to perform the complex, precision machining that is typical of present sculpture milling requirements in aerospace manufacturing.

In the course of their retrofit, three of the four machines have been given further advantages to increase their specific work capability. The rebuilding and modification necessary to incorporate numerical controls offered an opportunity to increase the size of the working surface (or otherwise increase the maximum size workpiece which could be accommodated) and to increase the spindle horsepower for greater metal-removal capacity. Two of the four machines were even changed in basic type--from conventional horizontal milling machines to horizontal spindle profilers. Some intrinsic machine defects dating from original manufacture were also corrected in the process of rebuilding.

### Performance

The K&T bed mill retrofitted with Bendix controls for MAC showed an accuracy of from  $\pm .0005$  to  $.0015$  inch in profiling aluminum (very good),<sup>1</sup> and within from  $\pm .003$  to  $.005$  inch in steel (good, better than average). Overshoot at 25 ipm was within  $.005$  inch including programmed slowdowns (worse than average using programmed slowdowns, but not serious). Many of the cutting test results were within the tolerances of the new, and more stringent, NAS 913, as were many of the machine alignments.

The Cincinnati bed-type milling machine retrofitted with Cincinnati controls for NAAC was generally within the tolerances for both alignment and cutting tests as specified by the latest revision of NAS 913, although the contractor specifications were somewhat less stringent. Accuracy was from  $\pm .001$  to  $.002$  inch in 2-dimensional profiling (good) and from  $\pm .002$  to  $.003$  inch in 3-dimensional machining of steel (average). Repetitive positioning accuracy in ten separately interpolated paths was usually within  $\pm .0002$  inch and never more than  $\pm .0007$  inch maximum (very good). Overshoot was less than  $.006$  inch at 25 ipm without programmed slowdown (very good).

The K&T #4 knee-type milling machine retrofitted with True-Trace controls has not yet been tested according to the NAS series of cutting tests. Sample production parts have been machined, however, to accuracies within  $\pm .008$  inch for complex aluminum parts having allowable tolerances of  $\pm .010$  inch and within  $\pm .012$  inch for a steel part carrying nominal tolerances of  $\pm .015$  inch. These results, however, include the effects of several known sources of error (which have since been alleviated) in programming and tape preparation. The part-to-part repeatability was within  $\pm .001$  inch (average).

The 3-spindle Cincinnati Hydro-Tel retrofitted with TRW controls for CVA was judged only marginal on the basis of its NAS performance test results. Nonetheless, it did demonstrate an accuracy capability of from  $\pm .001$  to  $.003$  inch in profiling steel (good). This machine experienced serious alignment difficulties upon reinstallation; all alignment and cutting tests probably should be repeated following whatever corrective action is taken.

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<sup>1</sup> Qualitative comparisons are based on evaluation survey reports of the performance of new profilers procured according to approximately the same NAS 913 specifications.

### Machine Age and Condition

Neither the age nor the original condition of the machines selected for retrofit proved a significant factor affecting the cost or performance of the completed retrofit systems, as had been anticipated by the earlier Institute study. Numerical control requires special types of servo-mechanism drives and a basic accuracy of machine alignment that is not generally found in conventional machines; thus, in most cases, considerable modification and probably some rebuilding would be required to retrofit even a new machine.

Retrofit will usually involve complete disassembly, some machining of basic machine parts, and the incorporation of new features as a part of the numerical control system, so that any additional effort required for complete renovation is relatively unimportant. Despite the fact that the BuWeps machine tools were from six to eighteen years old, the total retrofit costs would have been reduced by less than 5 percent and no significant accuracy or other performance differences would have been obtained had new machines in good condition (for conventional machining) been selected.

An important exception, however, concerns the extra effort which was necessary to rebuild the spindles of all four machines. The cost for spindle rework would not have been required had the machines been new and might not have been necessary had they actually been in good condition. Despite the fact that two of the four machines were listed in the BuWeps inventory as being in condition Code 01 or 02, both had serious spindle defects, one of which dated from the machine's original manufacture. In retrofitting any used machine, therefore, it will probably be either necessary or desirable to plan on thorough checking and/or rebuilding of the spindle as a matter of course.

### Life and Reliability

Despite the indications given in the Institute's previous report, retrofitted machines can have essentially the same life and reliability expectations as new machines. Point-by-point analysis of the rework, machine modifications, and equipment components of the four retrofitted machines indicates that the majority of key factors affecting life and reliability are on a par with those of new equipment.

For example, electric wiring, hydraulic lines, and much accessory equipment were replaced during rebuilding. Machine parts subject to wear, such as gears, bearings, and the surfaces of the machine ways,

were either restored or replaced to equal or exceed (as in the case of roller-contact ways substituted for sliding ways) new conditions. Spindle-drive motors were replaced on two machines, rebuilt for the other two. Servomechanism gear boxes and other drive components were new material in all cases. The electronic numerical control apparatus itself is new equipment in every respect.

The reliability and life expectations for a well engineered, thorough job of retrofit should be very nearly the same as that of new machines.

### Costs

The actual costs of retrofitting the four machines in the program exceeded the contract costs in all cases. Estimated costs for subsequent retrofit orders, however, are as follows:

<u>Contractor</u>	<u>Machine Tool (milling machines)</u>	<u>Control System</u>	<u>Estimated Costs for Repeat Order</u>		
			<u>Conversion</u>	<u>Controls</u>	<u>Total</u>
GAEC	K&T #4 knee-type	True-Trace	\$ 23,000	\$24,000 <sup>1</sup>	\$ 47,000
MAC	K&T 3' x 6' bed-type	Bendix	120,000	53,000	173,000
NAAC	Cincinnati 4' x 6' bed-type	Cincinnati	86,000	65,000 <sup>2</sup>	151,000
CVA	Cincinnati 28" x 60" 3-spindle bed-type	TRW	53,000	35,000	88,000

The machine conversion costs--rebuilding plus modification--range from 80 to more than 120 percent of the cost of comparable new conventional machines; this is at the upper end of the scale of values estimated in the previous study.

<sup>1</sup> Excluding cost of separate programmer unit for tape preparation (\$35,000) and shipping.

<sup>2</sup> Approximate, exclusive of special features.

Although exact counterparts do not exist for all of these original machines, the above costs for retrofit range generally from 65 to 80 percent of the cost of the most comparable new machines equipped with the same numerical control systems.

### Economic Feasibility

Final judgment as to the economic feasibility of retrofit depends upon the alternatives which are possible and the criteria adopted. It is clear that retrofit can offer machine performance closely approaching that of new equipment at savings in acquisition cost of 20 to 35 percent. Any conclusion concerning the over-all effectiveness of retrofitted equipment in production service must be deferred until the completion of the program and analysis of the production evaluation data. The adoption of any arbitrary criterion--such as retrofit is not feasible if it costs more than 50 percent of the cost of a new numerically controlled machine--has no apparent justification on the basis of information now available.

Preliminary estimates indicate that the Navy-owned inventory at airframe plants under BuWeps cognizance includes nearly 250 general purpose machine tools which might be retrofitted for profiling operations. Of these, approximately 100 are probably good potential retrofit candidates based on the general suitability of their basic designs. The desirability of undertaking a retrofit program of such a large magnitude, however, can only be determined in terms of the total effect upon BuWeps industrial production capability in relation to probable future requirements.

The BuWeps Retrofit Evaluation Program has nevertheless contributed significantly to the actual experience of retrofitting existing machines with numerical controls for production service (as distinguished from most previous examples of retrofit which were usually undertaken to prove developmental prototypes of system equipment). A number of other retrofit installations have also been carried out by other aerospace plants, and whatever additional experience is available from them will be incorporated in the Institute's final report.

### Retrofit Problems and Limitations

Despite the demonstrated progress of the BuWeps program and the growing number of retrofitted machines for production service, retrofit has still not fully achieved the status of an accomplished technical art. There are extremely few off-the-shelf retrofit kits available for specific makes and models of machine tools, and most of these are for point-to-point

positioning (AIA Class III) rather than continuous path (AIA Class IV). Most retrofit installations must, to a large extent, be custom engineered. Few, if any, numerical control systems have been designed to permit field installation by the user, and the development of adaptable servo-mechanism drive assemblies and components to facilitate the integration of electronic controls with a variety of machine tools is generally lacking.

The BuWeps program clearly indicates that successful retrofit depends on competent engineering skills in electronics, machine tool design and construction practices, and servomechanism systems. Most of the delays and setbacks contributing to the slow progress of the four BuWeps retrofit systems can be identified with engineering problems originating in one or more of these areas.

None of the four retrofits entirely escaped major technical problems which often necessitated appreciable engineering. There were few intrinsic difficulties attributable to the basic concept of retrofit itself, however, and relatively few problems occurred which proper engineering foresight could not have avoided. Rather, there were many detail problems in each application which required engineering solution during the course of the actual work. When the engineering was good, the final results were satisfactory and contributed valuable experience toward any future retrofit program.

The scarcity of qualified and interested retrofit sources continues to be a significant limitation to the more extensive application of retrofit numerical controls. The combination of engineering and fabrication capabilities required is seldom to be found in a single organization, whether an original equipment manufacturer (OEM) or, more particularly, a machinery rebuilder.

### III DESCRIPTION OF RETROFIT SYSTEMS

The four BuWeps retrofit numerically controlled machine tools conform generally to NAS 913<sup>1</sup> requirements as (issued 15 June 1955 and as amended 15 July 1959) for Type II profile milling machines for 360° plus depth, that is, 3-dimensional profile machining under numerical control. The numerical control systems, as retrofitted, provide full 3-axis continuous-path (AIA Class IV) control of machine motions and tape control of some auxiliary machine functions such as spindle and coolant.

#### Identification

The machine tools, control systems suppliers, retrofit integration sources, and contractors are as follows:

<u>BuWeps Contractor</u>	<u>Machine Tool</u>	<u>Control System</u>	<u>Retrofit Integration</u>
GAEC	K&T #4 vertical knee-type milling machine	True-Trace Corp.	True-Trace Corp.
MAC	K&T 2406 CSM bed-type horizontal milling machine	Bendix Corp.	Kearney & Trecker Corp.
NAAC	Cincinnati 36/72 Hydro-Tel bed-type horizontal milling machine	Cincinnati Milling Machine Co.	Cincinnati Milling Machine Co.
CVA	Cincinnati 28/60 Hydro-Tel 3-spindle bed-type vertical milling machine	Thompson Ramo Wooldridge, Inc. (TRW)	Raven Engineering Co.

<sup>1</sup> National Aircraft Standards, prepared by the Manufacturing Equipment Committee and published by the National Aircraft Standards Committee of the Aerospace Industries Association (AIA).

In all cases, the control system supplier held prime system responsibility under purchase order from the four respective contractors. Table I contains additional descriptive data on the four machine tools.

### Numerical Controls

The four numerical control systems selected for retrofitting to the machine tools provide for the automatic, fully coordinated control of all machine motions. That is, cutting paths requiring simultaneous movements of any or all three machine axes are generated and controlled precisely through a series of small, discrete, incremental steps (corresponding to the system resolution) generated from the condensed, numerically coded, input instructions. One system (True-Trace) performs this interpolation function in a separate piece of equipment known as a director--or programmer unit--whereas the other three systems generate the detail machine control signals directly in the machine control unit (MCU).

While all four of the control systems could conform to the NAS 943 specification for 1-inch-wide, 8-level punched tape with transverse binary coded decimal (BCD) format, only one of the four retrofit systems, (TRW), as procured, actually employs this input medium. Two of the systems (Bendix and True-Trace) employ 1-inch, 8-level punched tape input with a nonstandard data format; in one of these systems (True-Trace) the input tape is processed by the separate director unit into recorded control signals on magnetic film (35-mm sprocketed motion-picture type) used for machine control. The fourth system (Cincinnati) employs punched-card input which was specified at the option of the contractor for compatibility with other in-plant numerically controlled equipment.

Other characteristics of the numerical control systems are summarized in Table II. (It should be noted that all of the control systems could be supplied with many of the features listed in the table although they are not provided on the four retrofit machines described.)

Table I

MACHINE TOOL DESCRIPTION\*  
(NAS 913 Profiling Milling Machines, Type II, with AIA Class IV Numerical Controls)

Contractor	GAEC	MAC	NAAC	CVA
General Description (make and type)	K&T #4 vertical Knee Mill	K&T 2406 horizontal Bed Mill	Cincinnati 36/72 horizontal Hydro-Tel	3-spindle 28 x 60 vertical Hydro-Tel
Size				
Table width		36 in.	48 in.	28 in.
Table length		72 in.	72 in.	60 in.
Working height: min.	horizontal	9.87 in.	11.125 in.	} vertical
max.	vertical	16.87 in.	21 in.	
Travel				
Transverse (Y axis)	14 in.	36 in.	48 in.	24 in.
Longitudinal (X axis)		72 in.	72 in.	60 in.
Depth (Z axis)		7 in.	9.875 in.	14 in.
Feedrate				
Transverse	0 to 30 ipm	0 to 100 ipm	$\frac{1}{4}$ to 25 ipm	0 to 25 ipm
Longitudinal	0 to 30 ipm	0 to 100 ipm	$\frac{1}{4}$ to 25 ipm	0 to 25 ipm
Depth	0 to 30 ipm	0 to 60 ipm	$\frac{1}{4}$ to 25 ipm	0 to 12 $\frac{1}{2}$ ipm
Rapid Transverse (Tape Control)				
Longitudinal and transverse	0 to 60 ipm	100 ipm	100 ipm	200 ipm
Depth	0 to 60 ipm	60 ipm	30 ipm	
Spindle Data				
Horsepower	15 hp	15 hp	20 hp	20 hp
Speed Range	25 to 1250 rpm	25 to 1250 rpm	15 to 900 rpm	84 to 750 rpm
No. of Steps	32	32	24	16
Taper	#60/50 flange with #50 taper		#50	

\* Incomplete data.

Source: Manufacturer's data.

Table II  
NUMERICAL CONTROL SYSTEM DESCRIPTION

	GAEC	MAC	NAAC	CVA
Make and Type	True-Trace "True-Merical"	Bendix	Cincinnati "Digl-Log"	Thompson Ramo Wooldridge "DCS"
Control Media				
Machine input	7-level, 35mm magnetic film (sprocketed)	8-level, 1" punched mylar-aluminum foil	90-column punched cards (Remington Rand)	8-level, 1" punched paper tape
Data format	Variable frequency digital pulses	Axial binary	Coded fields, BCD	BCD incremental blocks
Interpolation	Separate programmer (director) unit Input: 8-level, 1" punched paper tape	MCU	MCU	MCU
Servomechanisms				
Power drive	Hydraulic valve and power cylinder	Electrohydraulic valve and hydraulic motor	Electrohydraulic valve and hydraulic motor	Electrohydraulic valve and hydraulic motor
Position measurement	Mechanical feedback from table to hydraulic tracer valve with stylus connected to precision instrument leadscrew driven from synchronous-motor differential gear unit	Magnetic pulse quantizer	Synchros plus special auto-transformers and stepless switching	Resolvers
Other feedback	None	Tachometer stabilization	Coarse/fine and extended range systems	Tachometer stabilization (optional)
System Resolution				
Quantization level	(.0035" at 30 ipm variable--depending on feedrate--down to .000013")	.0002"	1:100,000 (e.g., .001" in 100")	.0002"
Program increment		.0002"	.001"	.0001"
Style of Construction	Conventional transistorized	Modular vacuum tube	Conventional electromechanical vacuum tube	Modular transistorized
Auxiliary Functions				
Spindle				
On/off	Tape controlled	Tape controlled	Tape controlled	Tape controlled
Speed selection	Manual	Manual	Manual	Manual
Coolant	Tape controlled	Tape controlled	Tape controlled	Tape controlled
Chip removal system	None	None	None	None
Power drawbar	None	None	None	None
Tooling clamps or fixtures	None	None	None	None
Cutter change or selection	None	None	None	None
Other Features				
Program stops	Tape	Tape	Tape	Tape
Feedrate over-ride	±10%	20% to 100%	None	25% to 125%
Mirror image reversal	X, Y	X, Y	X, Y, Z	X, Y, Z
Zero shift range	Set point	Set point	±100% X, ±10% Y and Z	Set point
Position display	Mechanical dials on machine	Tape command data readout	Console indicator dials	None
Cutter compensation	None	None	±.999"	None
Operator instruction display	None	None	None	None

Source: Manufacturer's data.

#### IV MACHINE TOOL MODIFICATIONS FOR RETROFIT

The four machine tools were extensively overhauled and modified to incorporate numerical controls. In all cases the machines were completely dismantled and disassembled. Each machine was subjected to thorough engineering survey and analysis to determine the requirements for reconditioning or replacement and modifications to accept numerical control. Engineering tests were also made of one machine (MAC) to measure its structural adequacy experimentally and to determine certain constants affecting machine performance and the design of the servomechanism system.

##### Rebuilding

The rebuilding of all machines was thorough and complete. In essence, the rebuilding amounted to a complete restoration of the basic elements of all machines. It included the remachining, rescraping, and realignment of all major machine members in accordance with the tolerances specified by the contractors and/or control system engineers; these tolerances were generally much more stringent than those adhered to in the original manufacture of conventional machines of the several types represented. In most cases all bearings, wiring, and hydraulic lines were completely replaced. Structural members, gears, and other components were also replaced with new parts when examination disclosed excessive wear or other deterioration.

Spindle motors were rebuilt for two of the machines and replaced in the other two; one replacement provided increased spindle power and the other a lower power rating. It was necessary to completely dismantle and rebuild all of the spindle drives, despite the fact that two of the machines had been listed in the Navy inventory as being in Condition Code 01 and 02; the spindles of machines with this designation should not normally require rebuilding.

##### Machine Modifications

The modifications necessary to convert these standard types of machines for numerical control were also very extensive. Major structural alterations were made to three of the four machines and all machine-axis drive systems were completely revised and replaced for servo control.

The basic configurations of two machines (MAC and NAAC) were drastically changed by the addition of vertical angle-plate work tables that not only reorient the working surface from horizontal to vertical but also provide larger working surfaces than the machines had originally. These configurational changes led to other changes in the fundamental machine supporting structure and in the detail design of the table and bed ways.

The third extensively altered machine (CVA) was provided with a new, longer bed to eliminate sagging of the table at the extreme limits of travel. This effectively increased (by a factor of about two) the maximum length of workpiece which could be machined accurately (under single-spindle operation only, however.)

All four machines underwent complete replacement of the normal power drive trains with servomechanism systems to drive each axis of motion in response to the numerical control commands. The detail design of the machine ways was modified in three of the machines to incorporate rolling-contact bearings for reducing friction.

In all four machines, new accessory equipment for lubrication and automatically controlled coolant systems was added. Many other supporting detail changes were also made as required to accommodate numerical control.

A summary of the rebuilding and modification performed on each of the four retrofitted machines in the program is given in Table III.

Table III

SUMMARY OF RETROFIT MACHINE MODIFICATIONS  
AND REBUILDING

	GAEC	MAC	NAAC	CVA
Engineering	Survey and analysis	Survey and analysis plus stiffness tests	Survey and analysis	Survey and analysis
Major Modifications and Rebuilding				
Disassembly	100%	100%	100%	100%
Principal castings	Retained	Retained	New saddle required New table required Bed, column, and spindle carrier retained	New bed required Column, ram, and spindle housing retained
Structural changes	None required	Vertical angle plate added Roller bearing overarm support added Hydraulic piston center-balance installed under machine Spacer added between bed and column	Vertical angle plate added Counterbalance relocated	Air cylinder counterbalance added above spindle head
Way construction	Remachined and scraped to new tolerances	Hardened and ground way inserts and roller bearings added on X axis Remachined and scraped Y and Z axes to new tolerance	Hardened and ground way inserts and roller bearings added, 3 axes	Remachined and scraped to new tolerances Tac-Way roller bearing inserts added, 3 axes
Other Modifications				
Servomechanisms	Replace leadscrews and drives with hydraulic cylinders, 3 axes Add fittings, brackets, etc., to mount instrumentation leadscrews, hydraulic valves, and differential drive assemblies	Replace conventional leadscrews with ball/nut type, X and Y axes; with hydraulic cylinder, Z axis. Mount servo gear boxes, X and Y axes, special instrumentation assembly, Z axis	Replace conventional leadscrews with ball/nut type, 3 axes Mount servo gear boxes, including feedback instrumentation, 3 axes	Replace conventional leadscrews with ball/nut type, 3 axes Mount servo gear boxes, including feedback instrumentation, 3 axes
Pressure lubrication system	None required	Added	Added	Added
Automatic coolant system	Added	Added	Added	Added
Limit stop system	None required	Revised	Revised	Retained
Other Rebuilding				
Spindle				
Disassembly	100%	100%	100%	100%
New components	Bearings, brakes, belts, and some gears	As required	As required	As required
Remachining	Some, for truing-up	Reboring to correct .004" eccentricity	Some, for truing-up and to repair damage	Reboring and new quills for alignment
Drive motor	Rebuilt	New	Rebuilt, with flywheel added	New
Electrical panel and wiring	New	New	New	New
Hydraulic power lines and supply	New	New	New	New
Table	Rescraped	Rescraped	New	Rescraped
Finish	Fill and repaint	Fill and repaint	Fill and repaint	Fill and repaint

Source: Machine tool OEM's, rebuilders.

## V PERFORMANCE TESTS AND RESULTS

A basic requirement of the program as established by BuWeps was that each of the four retrofit machines should essentially conform to the performance specifications of NAS 909 and NAS 913 for 3-axis tracer and tape controlled profiling and contouring machines. The applicable performance specifications contained in NAS 913 include two series of tests: (1) tolerance tests dealing with the accuracy of machine alignments and (2) cutting tests covering machine operating performance under actual metal-cutting conditions.

Although NAS 913 has subsequently been revised, the issue which was current at the time of inception of the BuWeps program represents but a slight modification of tests which were designed and used by industry for many years in acceptance testing of tracer controlled machines. Nevertheless, this early version of NAS 913 (referred to herein as "AIA specifications" to differentiate it from the new, recently approved revision of NAS 913) was widely used in testing a large number of numerically controlled machines in the Air Force bulk procurement program. The BuWeps contractors adhered generally to these same requirements in their procurement specifications.

### Applicable Specifications

The pertinent tolerance specifications of both the AIA tests (old NAS 913) and the new NAS 913 tests are summarized in Tables IV-A and IV-B. The table entries also note the deviations from the AIA specifications which were embodied in the BuWeps contractors' purchase specifications for their respective retrofit machines. (These tables list only those test items which deviate significantly from the AIA specifications.) There were also other differences in the test procedures (types of cutters, spindle speeds, feedrates, and the like) and in the details of instrumentation and test methods due to differences in machine capabilities and the circumstances of the tests.

### Basis for Testing

Three machines (MAC, NAAC, and CVA) were tested according to the AIA specifications upon their completion at vendors' plants as a condition of acceptance prior to reinstallation at the contractors' plants. These three machines met the essential tolerances specified for both the alignment tests (Table IV-A) and cutting tests (Table IV-B).

Table IV-A  
SUMMARY OF ALIGNMENT TEST SPECIFICATIONS  
(Tolerances in Inches Except as Noted)

Test Number	Type of Test	AIA (old NAS 913)	New NAS 913	GAEC	MAC	NAAC	GVA
1.	Spindle to table runout, longitudinal	.001 per ft. .0025 total	.0005 per 18 in. .001	* <sup>1</sup>	*	.002 .005	*
2.	Spindle to table runout, transverse	.001 per ft. .0025 total	.0005 per 18 in. .001	*	*	.002 .005	*
3.	Vertical head movement square to table	.0006 max Check at 90°	.0004 per 12 in.	*	*	.0006 per ft.	.0006 per ft.
4.	Depth slide parallel to spindle	.001 per ft. Check at 90°	.0004 per 6 in.	*	*	.0006 per ft.	.0006 per ft.
5.	Slide displacement during locking	.001 at 12 in. Check at 90°	n.a. <sup>2</sup>	*	*	*	*
6.	Spindle face axial runout, (external)	.0004 max	.0002 TIR <sup>3</sup>	*	*	*	*
7.	Spindle face radial runout, (external)	.0004 max	.0002 TIR	*	*	*	*
8.	Spindle runout (internal)	.0005 at 1½ in. .001 at 12 in.	.0003 .0007	*	*	*	*
9.	Table square with spindle	n.a.	.0003 at 12 in. radius	n.a.	n.a.	n.a.	n.a.
10.	Table flatness	n.a.	.0005 per ft. .001 TIR transverse .0015 TIR longitudinal	n.a.	n.a.	n.a.	n.a.
11.	T-slot parallel to longitudinal axis	n.a.	.0005 per 18 in. .0015 over-all	n.a.	n.a.	n.a.	n.a.
12.	T-slot square with transverse axis	n.a.	.0005 per 18 in. .0015 over-all	n.a.	n.a.	n.a.	n.a.

<sup>1</sup> AIA specifications apply.

<sup>2</sup> n.a. means not applicable.

<sup>3</sup> Total indicator reading.

Source: Applicable specifications.

Table IV-B

**SUMMARY OF CUTTING TEST SPECIFICATIONS**  
(Tolerances in Inches Except as Noted)

Test Number	Type of Test	AIA (Old NAS 913)	New NAS 913	GAEC	MAC	NAAC	CVA
1	Maximum horsepower	$\pm .001$ per ft $\pm .003$ max (75% length) Note (a)	.0015 .005 * <sup>1</sup>	*	.0015 .005 115 $\mu$ in.	.002 .006 *	.0015 .005 (full length) *
2	Maximum feedrate	$\pm .001$ per ft $\pm .003$ max (75% length) Note (a)	.0015 .005 *	*	* * 115 $\mu$ in.	.002 .006 150 $\mu$ in.	.0015 .005 (full length) 160 $\mu$ in.
3	Parallelism and squareness	$\pm .0015$ per ft $\pm .005$ max (75% length) Note (a)	* * *	*	* * 105 $\mu$ in.	n.a. <sup>4</sup>	* * 60 $\mu$ in.
4A	360° plus depth (rectangular)	$\pm .005$ on periphery $\pm .005$ depth <sup>2</sup>	.0015 per ft .005 max <sup>3</sup>	*	*	.003 per ft .005 per ft <sup>3</sup>	n.a.
4B	*	Check at 90°	Check at 45° Also, Note (b)	*	*	Also, Note (a)	*
5	360° (circular segment)	$\pm .005$ total $\pm .010$ quadrant	n.a.	*	Also, finish 150 $\mu$ in.	.005 TIR <sup>5</sup> diameter .003 quadrant Also, Note (a)	* * Also, finish 60 $\mu$ in.
6	360° (circular)	$\pm .005$ max (inc. quadrant changes)	.002 radial .004 quadrant Also, Note (c)	*	* .010 quadrant Also, finish 150 $\mu$ in.	.005 TIR diameter .003 quadrant Also, Note (a)	* * Also, finish 60 $\mu$ in.
7	360° plus depth (circular)	$\pm .005$ diameter $\pm .005$ angle <sup>3</sup>	n.a.	*	.010 quadrant * Also, Note (a)	* .006 depth max Also, Note (a)	* * Also, finish 60 $\mu$ in.
8	360° square or rectangular (overshoot)	.003 at 10 ipm .006 at 25 ipm .012 at 60 ipm	.0015 at 10 ipm .002 at 25 ipm .004 at 60 ipm .012 at 100 ipm	*	* * .010 at 40 ipm	.006 at 25 ipm	n.a.
9	360° square or rectangular (undercut)	.006 at 25 ipm .012 at 50 ipm	n.a.	*	.010 at 40 ipm	.008 at 25 ipm	n.a.
10	Positioning (10 trips)	(no tolerance specified)	$\pm .0005$ 1st <sup>6</sup> $\pm .001$ 10th <sup>6</sup>	*	n.a.	.005 TIR max	*

<sup>1</sup> AIA specifications apply.<sup>2</sup> Normal to angle.<sup>3</sup> Normal to machine table.<sup>4</sup> n.a. means test not applicable.<sup>5</sup> Total Indicator Reading.<sup>6</sup> Each axis.

Notes: (a) Surface finish:	Type of Cut	High Speed (Aluminum)	Low Speed (Steel)
	Rough	100	150
	Finish	35	60

(b) Also surface finish as in (a); depth angle  $\pm .004$  per ft, and overshoot as specified under Test 8.

(c) Also mismatch at start and finish to tolerances specified for Tests 1 and 2.

Source: Applicable specifications.

Customarily, the alignment checks and some of the cutting tests were or will be repeated after reinstallation at the contractor's plants to verify the machine performance. The fourth machine (GAEC) was accepted at the vendor's plant on the basis of machining three sample airframe parts to production tolerances; this machine will be subjected to the entire NAS test series after its reinstallation at the contractor's plant.

#### Performance Test Results of GAEC Machine

The GAEC True-Trace machine has nevertheless satisfactorily demonstrated its capability for production machining of complex shapes. An irregular 2-dimensional steel part was machined with a maximum deviation of  $\pm 0.012$  inch from nominal drawing dimensions carrying a specified tolerance range of  $\pm 0.015$  inch. Two aluminum parts with complex 3-dimensional pockets were machined to within  $\pm 0.008$  inch where the tolerance specified was  $\pm 0.010$  inch. Part-to-part repeatability was measured and was within  $\pm 0.001$  inch on both types of material. Most of the measured deviations of both the steel and aluminum parts were generally within  $\pm 0.005$  inch or  $\pm 0.006$  inch.

The test part machining on this machine included several known sources of error due to cutter size deviation and defects in the programming. For example, excessively large feedrate steps programmed for acceleration and deceleration resulted in path closure errors of from  $.001$  inch to  $.002$  inch as measured at the machine; and arithmetic rounding errors in computation accumulated to total errors as large as  $.008$  inch in some of the repeated passes necessary to machine a deep pocket in one of the aluminum parts. Further refinement of the computer programming for the newly developed post-processor for this system has subsequently eliminated these computational difficulties.

The vendor's design intent was stated to be that this machine should be capable of producing parts to within  $\pm 0.002$  inch of nominal dimensions.

#### NAS Performance Test Results of MAC Machine

The K&T bed-type milling machine with Bendix controls for MAC produced very good test results. Some difficulties with the Z axis servo system caused large and obvious deviations in depth of cut, however, but these have subsequently been corrected.

Parallelism and squareness on basic cuts in steel (Tests 1, 2, and 3 in Table IV-B) were generally accurate within  $\pm 0.0005$  inch and the surface finish was excellent (30 to 50 microinches rms). Profiling cuts

(Tests 4, 5, 6, and 7) were typically within  $\pm .0015$  inch in aluminum and  $\pm .001$  inch in steel. These cutting test results generally conform to tolerances specified in the new NAS 913. Overshoot (Test 8) at 25 ipm was .004 inch (X axis) and .005 inch (Z axis) including programmed slowdowns.

This machine is capable of producing parts with comparable accuracy and surface finish from the same control tapes used by a similar new machine at MAC.

#### NAS Performance Test Results of NAAC Machine

The bed-type Cincinnati Hydro-Tel retrofitted with Cincinnati controls for NAAC likewise demonstrated good test results. Although some of the NAAC test specifications allowed greater tolerances than the AIA specifications, actual machine performance was usually well within the limits of the latter and actually met the requirements of the new NAS 913 in most respects.

All machine alignments were within  $\pm .001$  inch per foot and all but one (spindle internal runout) were within the limits of the new NAS 913 as well. The basic cutting test performance was also generally within or close to the new NAS 913 tolerances. Parallelism, squareness, and flatness were within  $\pm .002$  inch to  $\pm .003$  inch total (Table IV-B, Tests 1 through 3). Surface finish down to 40 to 60 microinches rms was obtained on some of the roughing cuts in steel. Difficulties experienced in developing full spindle horsepower (Test 1) were subsequently corrected by rebuilding the spindle drive. Profiling cuts (Tests 4 through 7) showed tolerances ranging from  $\pm .001$  inch to  $\pm .004$  inch for steel and had excellent surface finish in the 10 to 40 microinches rms range.

The blending of segments along curvilinear cutting paths was excellent, and there were no distinguishable variations noted at quadrant crossover points due to the parabolic interpolation feature of this control system. Also, the servo control was excellent, holding the overshoot (Test 8) to less than .006 inch at 25 ipm without benefit of any programmed slowdown. The repeat positioning test (Test 10) produced no deviation greater than .0007 inch, and only three out of approximately forty measurements in two axes varied by more than .0002 inch from the initial measured positions.

This machine also is capable of producing parts interchangeably--with comparable results--from the same control media used by similar new profilers at NAAC.

### NAS Performance Test Results of CVA Machine

The 3-spindle Hydro-Tel with TRW controls for CVA also has met the tolerance and cutting test specifications, although its performance was judged marginal on some of the tests. Serious alignment difficulties have been experienced in attempting to reinstall this machine, and the verification tests have not yet been performed at the contractor's plant.

The preliminary acceptance tests indicated profiling accuracy on the order of  $\pm .001$  inch to  $.003$  inch and surface finishes in the range 60 to 100 microinches rms in steel. Quadrant change deviations were very small.

This machine is currently in the process of realignment and reinstallation at CVA.

## VI RETROFIT COST INFORMATION

Preliminary cost information and estimated bid prices for repeat orders for comparable retrofit machines have been obtained for all four systems (see Table V). These data are subject to further refinement regarding their completeness and comparability. Since all of the BuWeps contract arrangements included spurious nonequipment items, and all of the equipment vendors encountered unforeseen delays and technical problems, the quotations for repeat orders are more meaningful than either the contract costs or actual costs.

### Machine Work Costs

The estimated repeat-order costs for machine rebuilding and modifications (including parts and materials) range from about 80 percent to more than 130 percent of the cost of the most comparable conventional manual machines. It is not possible to differentiate adequately between the cost of rebuilding and the cost of modifications.

The cost of the machine work in retrofit appears to be affected by such factors as (1) the size and complexity of the machine to be retrofitted, (2) the nature of the retrofitting source, original equipment manufacturer (OEM), or rebuilder, (3) the amount and nature of engineering work performed by the retrofit source rather than by the control system vendor, and (4) the kind of numerical control system (particularly the type of servomechanism system employed).

The original condition of the machine and the level of performance specified (speed, accuracy, surface finish) appear to have only relatively minor bearings on the cost of the machine rework required.

### Controls Cost

The cost of the control equipment is also an important factor in the total cost of retrofit. The cost of controls depends principally on (1) the system complexity and performance and (2) the engineering and service to be provided by the controls vendor. The latter can amount to as much as one-half of the manufacturing cost of the control equipment alone. Although the control equipment costs (as quoted for repeat orders) range from approximately \$24,250 (True-Trace system) to an estimated high of \$60,000 to \$65,000 (estimated for the Cincinnati system excluding optional features), the former system depends on an additional special equipment item (programmer) priced at approximately \$35,000 for tape preparation.

Table V

PRELIMINARY COST INFORMATION  
(Approximate Total Cost Breakdown, Including Machine Work, Controls, and Optional Features)

Contractor	Contract Amount	Actual Cost	Repeat-Order Estimate
GAEC	Machine	Engineering Machine work Basic Spindle (extra) Controls Parts and miscel- laneous Shipping Post-processor development	Machine work Controls Parts and miscel- laneous Shipping
		\$ 6,937	\$ 9,550
		32,330	24,250
		10,550	13,400
MAC	Parts programming and test machining	10,338	2,000 (var.)
		\$ 60,155	
			\$ 49,200
NAAG	Machine work	Engineering Machine work Materials and parts Controls and service	Machine work Materials and parts Controls and service
		\$ 60,000	\$ 90,000
		65,000	30,000
		\$125,000	52,750
CVA	Machine work and parts Card reader Angle plate Zero shift features and mirror image	(No data available)	Machine work and controls Card reader Angle plate Zero shift and mirror image features
		\$106,770	\$150,725
		8,460	8,460
		3,195	3,195
CVA	Machine work Controls and service Parts programming, data preparation and miscellaneous Post-processor development	27,670	2,620
		\$121,045	\$165,000
		\$ 42,500	\$ 42,500
		45,500	34,500
CVA			11,000
			\$ 88,000

\* Including parts.

Source: BuWeps contractors and equipment suppliers.

### System Cost Comparisons

Thus, it appears that the cost of retrofit is greatest for those numerical control systems that incorporate high performance servos requiring extensive applications engineering by the OEM or controls vendor. It should also be noted that retrofit installations predicated on this basis are most likely to achieve the best performance and machine capability.

Cost comparisons between the four BuWeps retrofit machines and other numerically controlled or conventional machines are not always possible because similar counterpart machines are not available in all cases. The two large profilers, the NAAC Cincinnati and the MAC Bendix retrofits, are most comparable to profilers procured between 1957 and 1959 as part of the Air Force bulk procurement program by the Air Materiel Command (AMC). Though procured from the same sources and with essentially the same control systems, the BuWeps machines are appreciably smaller (3 x 6 feet and 4 x 6 feet, respectively, as compared with 4 x 14 feet for the AMC machines), and this comparison is not strictly valid. The BuWeps retrofit machines nevertheless represent approximately a 30 to 35 percent lower cost than the AMC profilers which reportedly cost approximately \$250,000 each.

There is a more exact comparison for the NAAC Cincinnati retrofit machine, however. A similar numerically controlled model--comparable in terms of size, power, work capacity, and control characteristics--is listed by Cincinnati at \$210,000 including controls. A comparable conventional model with manual controls is priced at from \$95,000 to \$100,000 new. The repeat order quotation for retrofit is \$165,000, which is 22 percent less than the cost of the equivalent new machine, and only 65 to 70 percent greater than the manual machine.

The other two machines in the program, the GAEC True-Trace and the CVA TRW retrofits, do not have close counterparts. Both machines could be duplicated as new-machine types, however, by retrofitting new machines of the same makes and models. The results would not be significantly different unless alternative sources, other control systems, or different engineering approaches were to be introduced.

In the case of the GAEC True-Trace retrofit machine, a new K&T #4 knee-type milling machine is currently priced at approximately \$28,500 and it is estimated that the retrofitting of a new machine would be about \$5,000 less than the figure given in Table V because of the lesser amount of rebuilding required. The entire cost of the machine work required for rebuilding could not be saved, however, because it would probably still be necessary to rescope and realign the machine to the

closer tolerances required for numerical control. The cost to retrofit a new machine with the same controls would therefore be at least \$70,700 (less shipping). Retrofit thus represents a saving of about 33 percent over this alternative.

The 3-spindle Hydro-Tel with TRW controls for CVA originally cost nearly \$56,000; perhaps \$5,000 to \$8,000 could be saved over the estimated conversion cost if the machine were new. The resulting total cost for a comparable new machine would therefore be from about \$136,000 to \$139,000. The retrofit cost is 63 to 65 percent of these values.

Allowances for the trade-in or salvage value of existing machines have not been applied against the new machine costs in the foregoing examples. Any such value would tend to reduce the net acquisition cost of the new equipment correspondingly and decrease the percentage savings attributable to retrofit. At least three of the four machines in the BuWeps program had such a low realizable market value--less than \$200 each for the large bed-type milling machines (MAC and NAAC)--that salvage value was not a significant cost factor, as it might prove to be in other cases.

## VII INFLUENCE OF MACHINE CONDITION AND PERFORMANCE REQUIREMENTS ON RETROFIT COST

The extent to which the cost of retrofit would vary as a function of the original condition of the machine tool or of the performance specifications is considered a subject of interest for future retrofit procurement. It would be desirable, if possible, to reduce the cost of retrofit by selecting machines in good condition or by relaxing the specifications regarding alignment or performance. Conversely, substantial extra costs associated with machines in poor condition or with unduly stringent specifications would thus tend to limit the economic feasibility of retrofit. In either case, it would be useful to know how significantly the cost would vary for differences in machine condition or performance specifications.

### Machine Condition

The Institute's earlier study concluded that the cost of retrofit might be expected to vary directly according to the age and condition of the machine being retrofitted and that for this reason only machines which were relatively new (say less than six years old) or otherwise in good condition should be selected for retrofitting. The current program indicates that actually the age or condition of the machine only slightly increases the cost of retrofitting.

The age of the machine, of itself, has little bearing on either the costs or performance of the ultimate retrofit. All of the BuWeps machines were 5 or more years old at the time they were selected for the program; only one was less than 7 years old and the oldest was about 18 years old. In no case did the retrofit sources consider that the age of the machines had any direct effect on the cost or the work involved in retrofit. It was the consensus that the "date" of the original machine design would only affect specific details of the design or engineering necessary to modify the machine or to incorporate features required for numerical control. Even currently available models of machines comparable to those selected would require approximately the same considerations for retrofit as the machines actually retrofitted.

The original condition of the machines selected for retrofit--as regards wear, accuracy, and the like--also had only a slight influence on the ultimate cost or performance of the retrofitted machines. Since numerical control requires more accurate machine alignment and closer fitting of major machine parts than conventional machines, some rebuilding would usually be necessary even with a new machine. To ensure the basic

accuracy needed in all machine axes for numerical control, disassembly, some rescraping, and realignment are typically required; some major parts of new machines must be remachined as well, either for modification or for truing up. Thus, although badly worn machines would involve some greater effort for some of these tasks, the difference between the total effort needed for worn machines and that needed for new ones is not deemed significant. A used machine in good condition would still be reworked for more accurate alignment, along with any necessary modification, as a matter of insurance to obtain the best possible retrofit results.

The spindle drive system of a machine is one major element which would significantly affect the cost of retrofit. If the spindle is new or in good condition, it should not require rebuilding for retrofit. In the BuWeps program all four machines required spindle rebuilding despite the fact that all were intended to have been selected from the Navy-owned machine tool inventory as being in condition Code 01 (very good condition) or Code 02 (good condition). In fact, one machine listed as being in Code 01 had a spindle runout of about .004 inch, and another machine listed as Code 02 showed a spindle misalignment exceeding .010 inch per foot, a basic condition dating from its original manufacture. The other two machines were obviously not in either condition Code 01 or 02, but neither were they so listed in the inventory. Spindle rebuilding costs of \$3,600 to more than \$5,000 might have been avoided had these machines truly been in good condition.

#### Performance Requirements

To a large extent, the ultimate performance capability of a retrofitted machine is governed by engineering considerations which are inherent in (1) the original design of the machine tool, (2) the choice of the control system, and (3) the engineering approach to their integration. The integration of the original machine to numerical control capability establishes the general cost level of retrofit. Most of the work required is necessary to make the retrofit system work at all. The extra attention and greater care which mark a good job or the extra cost for high quality components affecting accuracy (leadscrews, gears, bearings, feedback units, and the like) add only a trivial amount to the total job cost. Reputable sources will generally endeavor to do the best job possible, and any relaxation of the performance specifications or tolerances from those which are intrinsically attainable will not necessarily achieve significant cost savings.

The BuWeps retrofit machines represent the best performance which could readily be achieved by the particular control systems selected under

the basic limitations of the original machine tool designs. These limitations are principally those governing the compromise of dynamic response under servo control--mass, stiffness, and friction effects.

With the exception of the GAEC True-Trace retrofit, the servo system design and machine tool modifications were dictated by the over-all requirements for integrating the numerical control systems with the machine tools by means of servomechanisms. Machine ways were changed from sliding surface contact to roller bearing contact to reduce stick/slip effects. Precision ball/nut leadscrews and servo gearboxes were installed to couple the control system drive and feedback components to the machine. These basic changes were, in each case, refined by engineering analysis and design attention to such details as the size, rigidity, and method of attachment of all structural and drive train parts. To do less would jeopardize the proper functioning of the system, and to do more would require extensive engineering design of all machine elements tantamount to new machine development.

Thus, the performance of three of the four machines in the program is most dependent on the systems engineering and is not greatly dependent on factors involving variable cost elements. Lesser specifications would not achieve significant cost savings, and even moderate performance improvements could be achieved only by inordinate increases in costs.

The GAEC True-Trace retrofit must be considered separately as a special case. This particular control system is based on a fundamental concept aimed at low cost and modest performance. In this system, several subsystems are cascaded so that improvements in individual subsystems can be made--with additional cost and effort--to improve the over-all system performance. The precision instrument leadscrews, for example, are an important determinant of the over-all accuracy. As retrofitted, the leadscrews on this machine are accurate to within  $\pm .0008$  inch and cost approximately \$1,000 each. For approximately double this cost, they could be procured with an accuracy of about  $\pm .0004$  inch. Also, the accuracy of the hydraulic control valves could probably be improved by about .0002 inch by applying selective manufacturing techniques and closer tolerances which would increase the total cost of the valves by about \$500. Additional effort and care in machine rebuilding, amounting to about \$1,500, could also be applied to improve the accuracy of the basic machine.

These possible areas of improvement in the True-Trace system would cost an additional \$5,000 (approximately 10 percent of the total retrofit cost) and might improve the over-all system accuracy from

about  $\pm 0.002$  inch (present stated system capability) to  $\pm 0.001$  to  $.0015$  inch. Beyond this, any further improvement in system performance or accuracy would probably require major changes in other areas such as (1) increasing the control system supply frequency from 60 cycles to 400 cycles, (2) redesigning the leadscrew drive system for increased response, (3) replacing the spindle drive motor with one of a higher speed rating to improve surface finish capabilities, and (4) improving the computer post-processor subroutine to permit faster accelerations and decelerations. No estimates have been made as to the cost or probable degree of improvement which might be associated with these refinements; in fact, the actual capability of this system as retrofitted has yet to be measured according to the NAS 913 series of tests.